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A review of energy characteristic of vertical greenery systems

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ABSTRACT

Rapidly growing cities and human activities change the environment and are accompanied by some drawbacks. Sustainable remedies are needed to protect the environment and the earth against warming environment, pollution, natural resource use and other negative aspects of human activities. Applying vertical greenery systems not only reduce temperature, but also have many economic, environmental and social benefits. This review is about vertical greenery systems description, division and benefits with a focus on energy related topics. The paper describes different experiments on vertical greenery systems by attention to their energy characteristic from recent years. Scan research and studies have determined positive aspects of these sustainable systems as well as a few negative aspects. Moreover, different parameters which are involved in thermal performance of vertical greenery systems are highlighted. Based on various scan research some recommendations for future studies are proposed.

Contents

1. Introduction

Urbanization and rapidly growing population change city features and convert them to concrete jungles [1]. Migration into urban areas and growing population lead to some problems like

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Table 1
Reviews on vertical greenery systems.

Name	Type of Manuscript	Objective
Kohler, 2008	Review	Vertical greenery systems technology with a focus on Germany
Yu, 2009	Review	Greenery in urban areas based on both systematic and thermal benefits
Hunter, 2014	Review	Thermal performance of green facades/quantify study
Jaafar, 2011	Literatures	Vertical greenery systems heat reduction
Perini, 2011	Literatures	General information
Loh, 2008	Literatures	General information
Bennett, 2012	Literatures	General information
Nafici, 2012	Literatures	General information
Shiah, 2011	Report	Potential feasibility and significant factors of installing vertical greenery systems

air, noise, and water pollution, increase concrete buildings and hard surfaces, lack of vegetation, increasing urban heat island, global warming etc. [1–8]. Increased air temperature leads to growing discomfort in indoor environments [9,10]. Applying sustainable methods in the form of greenery systems and applying these systems to buildings is an intelligent way to mitigate some of these drawbacks, and can mitigate depletion of resources [11].

Using renewable energy is a practice toward sustainability and is suitable for developing countries without clean energy [12] although this is applicable for developed nations as well. Some important renewable energy systems are ground source-based systems, day-lighting systems, and solar-based energy systems [13]. Solar energy is a powerful source to mitigate energy problems [14], and there are some ways to utilize solar energy like solar panels [15], solar walls [16], trump walls [17] etc. Although the sun is the main source of natural energy in the world, its radiation heats the environments and leads to increased temperatures. Therefore, solar energy should be controlled, because if it is not controlled correctly it has a negative warming effect. Using plants and greenery is an ecological solution to control solar radiation and reduce temperature. Moreover, the use of plants offers natural advantages as plants are a clean source [1,6].

Plants and greenery have numerous benefits for urban areas and environment [18–24]. To illustrate, in external spaces, plants are natural tools for controlling microclimatic condition by their shading effects, absorption and reflection abilities [25,26]. It is proved that small green areas spaced at appropriate intervals help to cool surroundings [27], and an experiment confirms this claim and reveals direct connection between temperature and green areas [21]. Applying greenery on unused building surfaces is a way to integrate urban areas and plants [28]. It is an answer to heavy population and high cost of land that prevent city habitants from having enough public green spaces on the ground [6,29]. Moreover, the greenery benefits buildings and structures, because all buildings and its surrounding areas act as closed working systems [30]. Applying green roofs and vertical greenery systems are appropriate ways to use greenery systems in buildings. Controlling temperature by green roofs is becoming common and valuable research have been done [6,31–34], but using vertical greenery systems to control temperature is a new idea and requires more consideration [35]. Specifically, vertical greenery systems require special techniques and systems in implementing on buildings, where these techniques and systems will have different influences on building performance.

Attention to vertical greenery systems is drawing attention from different points of views. Kohler [36] reviewed research activities on green walls and green facades technology with a focus on Germany. Yu [37] provided a comprehensive review on greenery in urban areas based on both systematic and thermal benefits and divided these greeneries into public green areas, rooftop gardens and vertical landscaping. Moreover, there is a peer-review on thermal performance of green facades in quantify point [38]. It compared related studies and experiments and found some research design problems and missed issues in the studies such as lack of microclimatic information, plants properties, or green facade design components. Jaafar [39] conducted a literature review on vertical greenery systems with a focus on vertical greenery system heat reduction. In addition to these reviews, there are some literatures about vertical greenery systems [40–42]. Moreover, Bennett [43] has provided an overview on green facade, and there is also a general writing about the impact of green roof and green facade on urban agriculture [7]. Apart from that, there is a report written by researchers at the University of British Columbia about the potential feasibility and significant factors of installing vertical greenery systems [44]. Table 1 compares the objectives of reviews and writings on vertical greenery systems.

These writings show that studies about vertical greenery systems are developing and attempts are underway to find ways for improving these system performances to control urban as well as environmental problems. Energy aspects and temperature reduction ability of vertical greenery systems are significant points, and study about them are important to optimize vertical greenery systems thermal performances.

Current review is focused on the energy aspects of vertical greenery systems. Observing and tracing recent studies and experiments on temperature and energy characteristics of vertical greenery systems is the main objective of this article. The focus is on the effects of different parameters that are involved in the vertical greenery system performances, and also applying new methods to improve their efficiency. For this aim, definitions, terminology and division of vertical greenery systems are offered. Afterwards, the benefits of these systems are described, and then different research about plants properties and growth are presented. Studies into vertical greenery systems energy reduction are then presented and the studies on different parameters that are effective in vertical greenery systems thermal performances are described. The summary emphasizes current state of research gaps and possible future research areas on vertical greenery system.

2. Materials and method

In the first step, this article presents a comprehensive literature review on vertical greenery systems definitions, terminology, classifications, and benefits. The study resources was formed from different source types such as journals, conference papers, theses, books as well as one standard, one report, and one serial. Most of them are up to date manuscripts and they are related to recent years. To evaluate thermal performance and energy characteristic of vertical greenery systems 22 peer-reviewed papers were scanned from 2005 to 2014 to ensure the most updated data on vertical greenery systems. They consist of 18 journals, 3 master theses, and one conference paper (Table 2). Several papers consisted of more

Table 2
Vertical greenery systems studies reviewed.

Name	Methodology	Climate – Regions	Reference Type
Wong, 2010	Perception studies	Tropical – Singapore	Journal
Yuen, 2005	Perception studies	Tropical – Singapore	Journal
White, 2011	Perception studies	Online survey questionnaire	Journal
Perez, 2011	Experimental test	Dry Mediterranean – Spain	Journal
Sunakorn, 2011	Experimental test	Tropical – Thailand	Journal
Ip, 2010	Experimental test	Oceanic – south coast of the UK	Journal
Eumorfopoulou, 2009	Test on real case	Mediterranean – Greece	Journal
Wong, 2009	Simulation	Tropical – Singapore	Journal
Alexandri, 2008	Simulation	9 Different cities	Journal
Wong, 2010	Test on real case	Tropical – Singapore	Journal
Perini, 2011	Test on real case	Maritime – Netherland	Journal
Jaffar, 2013	Test on real case	Tropical – Malaysia	Journal
Taib, 2010	Test on real case	Tropical – Malaysia	Journal
Kontoleon, 2010	Experimental test and simulation	Mediterranean – Greece	Journal
Stec, 2005	Experimental test	Laboratory condition	Journal
Li, 2010	Perception study	Humid sub-tropical, Hong Kong, China	Journal
Wong, 2010	Test on real case	Tropical – Singapore	Journal
Franco, 2012	Experimental test	Laboratory condition	Journal
Binabid, 2010	Test on real case	Moderate to hot – California, USA	Master thesis
Price, 2010	Experimental test	Humid sub-tropical, USA	Master thesis
Schumann, 2007	Experimental test	Humid sub-tropical, USA	Master thesis
Rayner, 2010	Existing living wall	Moderate oceanic – Australia	Conference paper

than one study. These studies were scanned separately for the purposes of this review, forming a total of 29 studies.

3. Definitions and classifications of vertical greenery systems

Plants grown on vertical surfaces are called vertical greenery systems [44,45]. In this way one or several kinds of vegetation can grow vertically on a surface whether naturally or made by humans either inside or outside the building [42,46], attached to the wall of the building or standing independently in front of the wall [45,47]. In brief, vertical greenery systems are described as growing each kind of plants on each kind of vertical surface [35,46,48,49].

Different names and terminologies were used to define these systems [50]. Table 3 presents different terminologies of these systems, but vertical greenery system is a comprehensive and commonly used term.

There are different classifications for vertical greenery systems. One such classification system is based on growing media, construction methods, and also plants species [37]. It divided vertical greenery systems into four categories: tree-against-wall type; wall-climbing type; hanging-down type and module type (Fig. 1). Tree-against-wall types are not really vertical greenery systems, but their performances are the same. In wall-climbing types, which are common in traditional architecture, plants can cover wall surfaces directly or use trellises to climb. Using wall climbing is easy, but it takes time to cover entire facade surfaces with greenery. Hanging-down types are made by plants with long pedicel on the balconies or on top of the buildings. This kind is something between green roof and green facade. By using hanging-down type in each level of the buildings all facades will be green in a short time; moreover, by using different kinds of plants the facade will be colorful and visually attractive. The last one, module type, is a new technique. Fast growing, colorful, diverse, attractive and easy to replace spoil and withered plants are some module type advantages [37].

In all classifications the location of growing media plays a significant role in the type of vertical greenery systems. Growing media is the place that plant roots find nutrition [46]. It is possible for growing media to stay on the ground and only plants grow vertically and cover the vertical surfaces [39,40,46,47,51]. It is called green facade, and common in traditional architecture [35]. Moreover, it is possible for growing media stand vertically in front of the vertical surfaces [39,40,46,47,51]. It is called living wall, and it is modern technique. In living walls substrates stand vertically and hold growing media in carriers, therefore living walls are able to host a greater diversify of plants. Common systems for living walls are panel, felt or container systems [45,52]. Panel systems are pre-planted panels that are attached to the structures. Felt systems consist of felt pockets filled by plants and attached to the waterproof walls connected to the structures. In container systems plants are potted in containers and climb the trellises.

Table 3
Terminology of vertical greenery system [50].

Terminology	
Vertical greenery system	[49,58,46,48]
Vertical garden	[86,46,56,40,59,72,94]
Green vertical system	[53]
Green wall	[51,46]
Vertical green	[40,94]
Bio shader	[97]
Vertical landscaping	[46]

There are different names for green facades and living walls [50]. Green vertical system [53], support system [39], and facade greening [40] are commonly applied terms for green facades, and vertical garden [46], carrier system [39] and bio-wall [46] are commonly applied terms for living walls. Table 4 presents dichotomy of vertical greenery systems and their terminology.

Hunter [38] has a sub-classification for green facades based on the location of greeneries and wall surfaces as direct green facades and double-skin green facades (Fig. 2). In direct green facade self-clinging climbers are attached to the vertical surfaces while in double-skin green facades engineering support structures assist plants to grow vertically.

This sub-classification is expandable for living wall systems. Therefore, it can be said that dichotomy of vertical greenery systems to green facades and living walls is the main classification covering other classifications, and it is agreed by most of the researchers.

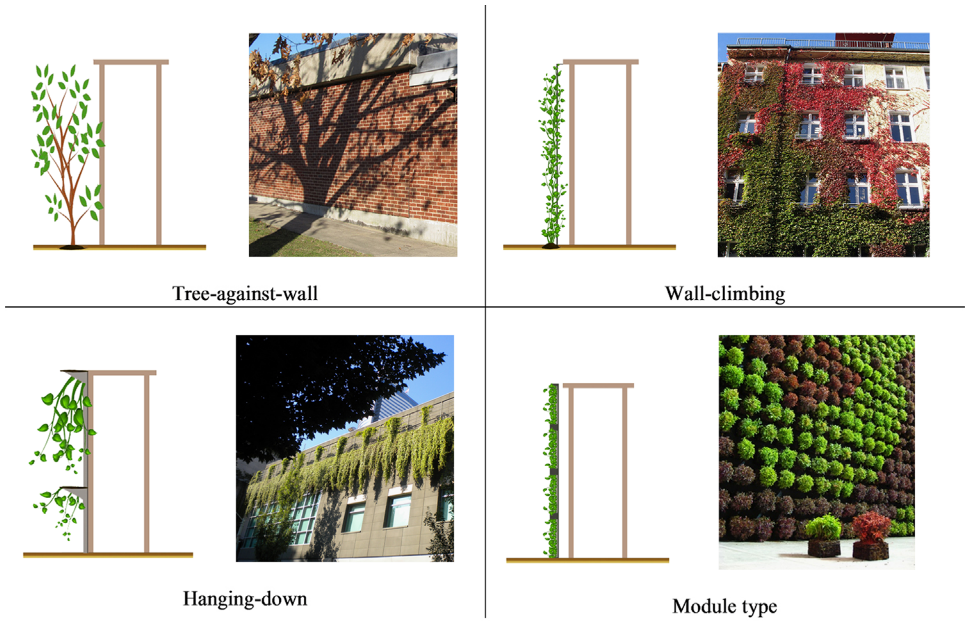
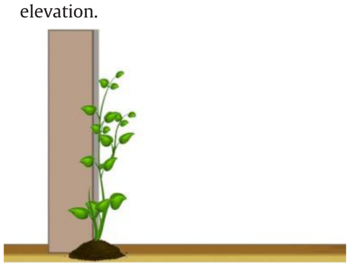
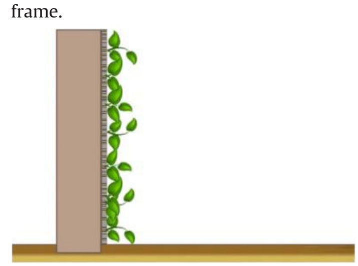


Fig. 1. Four groups of vertical greenery systems based on Yu [37] idea.

Table 4
Dichotomy of vertical greenery systems [50].

Green facade		Living wall	
In green facade, plants are rooted on the ground in soil and climb on facade and covers elevation.		Living walls are pre-vegetated sheets that are attached to a structural wall or frame.	
			
Terminology		**Terminology**	
Green facade/green wall	[36,39,51,40,94,53]	**Living wall**	[62,39,51,40,94,53]
Green vertical system	[53]	**Vertical garden**	[46]
Support system	[39]	**Carrier system**	[39]
Facade greening	[40,94]	**Bio-wall**	[46]

Selecting proper kind of vertical greenery system, green facade or living wall, depends on the purpose of installation, climate, facilities, budget etc. However, both of them have numerous benefits for the environment as well as the buildings and inhabitants.

4. Benefits of vertical greenery systems

The benefits of vertical greenery systems are divided into three parts: environmental; economic; and social benefits [39,44,51,54].

4.1. Environmental benefits

Vertical greenery systems have abundant environmental benefits. For example, plants on vertical landscaping absorb dust and clean the air [24,41], and in this way they work as natural air filtration. Moreover, based on plant photosynthesis, plants consume carbon dioxide and release oxygen [9,55,56]. This makes the air fresh and reduces carbon dioxide emission. Carbon dioxide covers the earth surface like a blanket and it causes the earth to grow warmer [10]. Moreover, it leads to increase important greenhouse gas expansion in the atmosphere [57]. Another important environmental benefit of vertical greenery systems is their ability to control noise and their use as barriers for noise abeyance [5,58]. They are also able to reduce sound reflection and reduce noise disturbance [44].

4.2. Economic benefits

In modern life attention to economic benefits of vertical greenery systems is expanding. One way is using vertical greenery systems as window shadings [59]. Increasing daylight and decreasing discomfort glare are the properties of appropriate shading systems [60] which are prepared by vertical greenery systems, and they eventually lead to reduced electricity demand. Moreover, they can act as spongy surfaces and control storm waters [61]. Vertical greenery systems are suitable for retrofitting projects as eco-retrofitting which has human and environmental amelioration aim, and it is more economical than demolition and reconstruction [62].

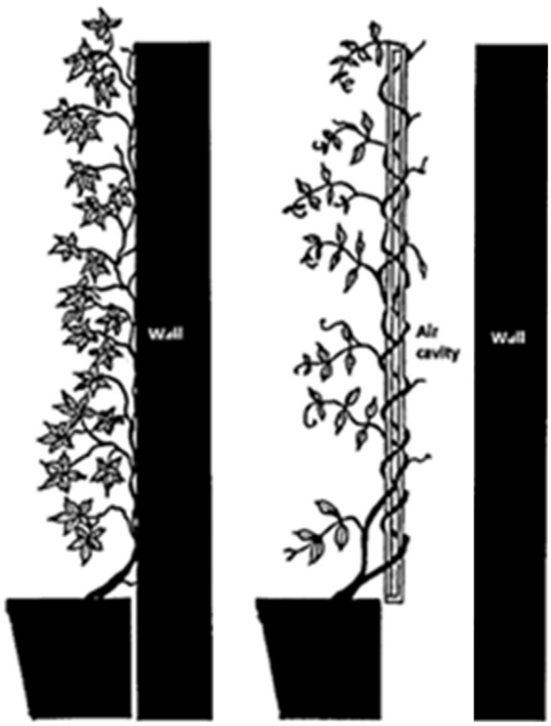


Fig. 2. Direct green facade (left) and double-skin green facade (right) [38].

In addition to the many economic advantages of vertical greenery systems, one important benefit is temperature reduction [43]. Temperature is the main criteria of human comfort [11] which is affected by human life-style. Different factors like function, social culture, esthetic factors, environment and technology effect on building envelope design [63], but modern building materials like concrete hold heat during the day more than rural areas [64]. Hard and impermeable surfaces like concrete and asphalt not only absorb solar radiation, but also reradiate it to the atmosphere [65]. Absorption and re-radiated solar energy are the main sources of high temperature, especially in urban areas [66]. It leads to urban heat island which is a significant problem in cities and urban areas. Urban heat island is the maximum temperature difference between urban areas and rural areas [67,68]. Applying vegetated areas in cities have crucial effects on reducing urban heat island, because plants absorb short wave radiation [69], and reduce solar re-radiation from hard surfaces [70]. Moreover, they make the environment cool by plants shading effects [59,71], evaporation and transpiration [69,72–76]. Accordingly, installing vertical greenery systems is an appropriate way to reduce urban heat island in crowded urban areas [72,74,76], as well as green roofs [64,69,77,78]. There are some research about the effects of urban greeneries and green roofs on reducing urban heat island [21,23,79], but the effects of vertical greenery systems on urban heat island reduction and temperature reduction need more research. Vertical greenery system more over reduces the temperature of cities and reduce urban heat island, reduce the temperature of a building or a structure that vertical greenery system is installed on [49,80]. Due to the ability of vertical greenery systems to reduce temperature, they are suitable systems for reducing cooling energy demand and improving energy efficiency of buildings.

4.3. Social benefits

Applying vertical greenery systems for its social benefits dates back to ancient time and Babylon Hanging Garden is one of the famous examples [44,46,65,81]. People used greeneries in buildings and their living areas in different forms for their esthetic sense, because connecting to nature is biologically innate. Plants create places for recreation and rest [82,83], and it is proved that contact with nature has psychological impact and increases human health and wellbeing [84]. In addition, reduced stress and lower obesity are achieved by proximity to green areas [85]. Accordingly, humans naturally request compound greenery in cities and urban areas and change gray and soulless surfaces to green screens. An online survey questionnaire comparing one house without any greenery and with different greenery position shows that houses with green facade are esthetically pleasing for all respondents [82]. It proves the idea of Blanc [86] that plants in urban areas and compound by buildings attract people more than plants in gardens. Apart from social benefits, it is important to make people aware of the economic and environmental benefits of vertical greenery systems.

4.4. General awareness about the benefits of vertical greenery systems

Commonly in greenery topics perception studies are formed based on respondents' esthetic sense and the focus is based on their desire for greenery areas, location, or the species of plants [82,87]. There are few studies concerning people awareness about the economic and environmental benefits of vertical greenery systems. To understand people's awareness of the advantages vertical greenery systems a survey questionnaire was formed in Singapore [81]. The respondents who were selected from different populations did not agree that vertical greenery systems have positive effects on reducing cooling energy demand by insulating. They also believed that vertical greenery systems cannot lengthen the building life, filter rain water and enhance water quality or control storm water [81]. Alongside vertical greenery systems benefits, the results of another study showed that people are also not aware enough about the benefits of green roof systems, and some people did not know anything about green roof system installed on their building [88].

Public awareness about the application and benefits of these systems is needed to utilize greeneries on buildings. Lack of public information about vertical greenery systems economic and environmental benefits cause landlords and investors to not request the installation of vertical greenery systems because of their initial cost, but actually, their installation has relatively low cost with numerous benefits [89]. Reducing temperature and economic benefits of vertical greenery systems are not popular like its esthetic impact, and people usually use these systems for their graceful features. New movement to utilize these systems based on their economic and environmental benefits is needed to employ them as effective elements for reducing temperature and cooling energy demand.

5. Selecting suitable plants for vertical greenery systems

Selecting appropriate vegetation for vertical greenery systems is the key for the survival of these systems. It needs the study on plants life, growth, and the manner that they adapt themselves to environment and helps to decide which kinds of plants are suitable in certain climates. These studies are more important for exterior plants, because some kinds of plants can live in one climate and some others cannot [46]. Apart from that, irrigation system, maintenance and installation methods are other reasons that influence the performance of vertical greenery systems [90]. The above was proven by an experiment conducted at Council House2 (CH2) in central Melbourne, Australia [90], which included

90 modular planters on vertical system. After two years, 60% of the plants died due to selection of inappropriate plant type. Table 5 presents the summary of plant failure.

Selecting suitable plants for certain purposes influence the performance of vertical greenery systems and improve the systems efficiency. Although the growth process for both green facades and living walls need surveillance, the criteria for selecting suitable plants are different. For green facades vine family with long stalk are appropriate, and usually they are selected for covering a green facade. Several research have experimented on growth process and plant density on green facade and their influence on performance variables. Experiment conducted in tropical climate of Thailand studied plant species Blue trumpet vine (*Thunbergia grandiflora*), Ivy gourd (*Coccinia grandis*) and Mexican creeper (*Antigonon leptopus*) (Fig. 3). After growth it was found that Blue trumpet vine grew very fast and gave a consistent density and filled leave coverage through minimum pruning, therefore it can be said that Blue trumpet vine is a suitable plant for covering green facade in tropical climate [91].

Climatic condition is an effective parameter to decide about selecting appropriate plant species for one region, and it should be tested separately for each region and climate. As an illustration, an experiment in dry Mediterranean Continental climate studied plant growth on a trellis and compared the ability of providing shade of four climbing species such as Ivy, Honeysuckle, Virginia creeper and Clematis [53]. The key variables of the above research were to determine the temperature reduction by different size of shadow created by plant types. Ivy and Honeysuckle had the best growth in height, but Honeysuckle in some areas had less density of foliage. Virginia creeper had better density of foliage, but in the first year this type of plant grows slow on trellis. Furthermore, Clematis was not suitable for Continental Mediterranean climate and had the worst growth [53]. Similar study in another region in Maryland, USA comparing the growth process of different vines on green clocks showed another results [92]. It was shown that Virginia creeper and Trumpet creeper are the best plants for climbing and covering trellises in terms of leaf area index and plant density.

Leaf area index is a common biological parameter defined by single side leaf area per unit ground area [54], and also considered planting species, planting distance and canopy area [93]. Several research use Leaf Area Index of plants to determine its influence on several performance variables, but in some studies measuring Leaf Area Index is not available and researchers introduce plants qualities in different ways. For example, Sunakorn [91] mentioned the quality of green facades by the percentage of plants covered on the trellises and the number of leaves layers, while Perini [94] described the quality of green facades by plants thicknesses. Sometimes the thickness of plants and substrate [95], or plants and panel size [96] are measured, and sometimes the density and shadow factors [53] are introduced. Criteria to measure the quality of plants on vertical greenery systems is different from one test to another, and is related to different kinds of climbers, plants species, trellises, substrate and others.

In total, appropriate plants with high Leaf Area Index can improve vertical greenery system performance. The results of an experiment in the UK by attention to incident and transmitted solar radiation extensively show that leaf area index of 5 resulted in12% coefficient bio-shading [97]. Although two or three years are needed to have a canopy with 5 Leaf Area Index which is the maximum rate [92], mixing different kinds of plants helps to have denser canopy in limited time. Accordingly, based on different shape and size of leaves, they can grow in between large leaves and fill their gap and provide a dense green facade.

These studies reveal the importance of plant quality and adaptation in certain climates and weather conditions for its growth process and covering the wall surfaces. By attention to experiments it can be understood that vine family are common plants for green facades, but limited experiments have investigated plants growth and species in living walls. Although plants species for living walls can be selected in wider range than the

Table 5
Total plant failure of vertical greenery system at Council House2 based on death and poor plant cover [90].

Species	No. planted[a]	Plant death		Poor cover		Plant failure	
		No.	%	No.	%	Total No.	Total %
Clematis aristata	14	10	71.4	1	7.1	11	78.6
Kennedia nigricans	41	22	53.6	12	29.3	34	82.9
Kennedia rubicunda	51	15	29.4	11	21.6	26	50.9
Pandorea pandorana	16	1	6.2	0	0	1	6.2
Trachelospermum jasminoides	42	22	52.4	6	14.3	28	66.6
Total	164	70	42.6	30	18.3	100	60.9

[a] At August, 2006.

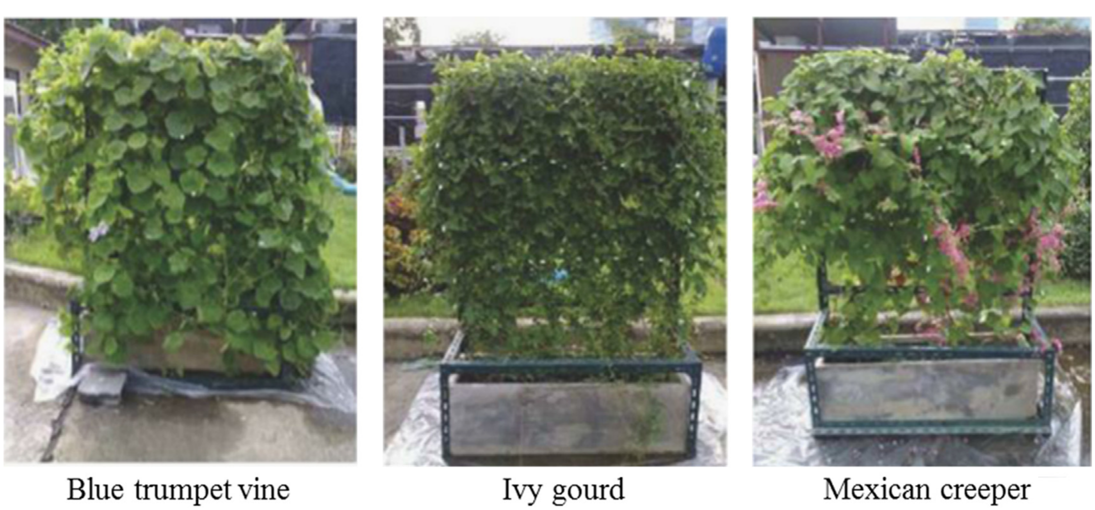


Fig. 3. Plant growth comparison for three green facades [91].

green facades, and are not limited to plants with long stalks, their applications, properties, substrate structures, and other maintenance qualifications require additional study.

6. Energy reduction of vertical greenery systems

The sun is the main source of energy in the world and solar energy is the most effective architectural environmental factor that influences both inside and outside the buildings [98]. Installing plants and vegetation on the building surfaces in the form of vertical greenery systems reduce the temperature of buildings as well as the environment. The studies about vertical greenery systems thermal performances and different factors that are effective in the performances of these systems such as orientation, ventilation or combination with some architectural features are conducted by researchers in different climates around the world.

6.1. Temperature reduction and cooling effects of vertical greenery systems

Temperature reduction is one of the important properties of vertical greenery systems. Moreover shading effects, cooling effects of plants are effective in temperature reduction. It helps to reduce cooling energy demand and energy consumption. The ability of a building to operate and function with minimum energy consumption is energy efficiency [99]. This section reviews several research that apply vertical greenery system in reducing temperature, energy consumption and cooling energy demand.

Several research were conducted to determine the effectiveness of vertical greenery systems and their influence on thermal transfer value, energy consumption, cooling effect, temperature variation and so on. These studies range under different climatic conditions. In Mediterranean region of Greece during cooling period, a thermal comparison between a bare wall and a wall covered with a green facade was formed to show the dynamic thermal characteristics and temperature variation. The results show that covering the wall surface with plants has thermal benefits for both exterior and interior surfaces, and it has reduction effect on heat flow losses [80]. Thermal effects of plants on walls of buildings were tested in an experiment in Singapore [49] to understand temperature and energy consumption of vertical greenery systems. By using TAS simulation software a ten storey hypothetical designed building was simulated in three scenarios: one with opaque walls, one with seven windows in each storey and one with full glass cover (Fig. 4). These scenarios were compared to similar situations by adding vertical greenery systems. Indoor mean radiant temperature and the energy cooling load were measured. Based on a hypothetical designed building in tropical climate it was found that heat transfer through concrete wall is reduced by using a cover of plants. Vertical greenery systems reduce excessive solar energy to the building wall, and they are useful for concrete buildings. Moreover they reduce thermal transfer from transparent surfaces. Glass facades with 100% cover of vertical greenery system reduce mean radiant temperature effectively. Using vertical greenery system reduce thermal transfer value for full glass facades [49].

The results of vertical greenery systems simulation tests highlight the potential of these systems in reducing energy consumption [49], but there has been little emphasis on the results of vertical greenery systems simulation tests and they are few in number. The common method to examine greenery systems thermal performances is using natural plants whether in real cases or small-scale models. The temperature reduction ability of vertical greenery systems was tested based on a real green facade installed on a third floor of a parking structure in moderate to hot climate of California [46]. The results revealed the green facade ability to reduce temperature and showed that the temperature behind the green facade was lower than the area without greenery. Moreover real cases, small-scale models are used to test temperature reduction ability of vertical greenery systems. This method is useful especially to study interior thermal changes based on vertical greenery systems, because variables are more controllable than other methods. In Pomona in the United States two sample boxes were established to compare temperature reduction ability of living walls [46]. One of them had no greenery and was used as a benchmark and another was covered with a living wall. The first time the living wall covered 100% of wall surface and in another it covered 75% of the surface. The results show that installing living wall is effective to reduce indoor temperature and denser plant coverage improves the temperature reduction rate [46]. In another experiment inside temperature of one test box which was covered with a modular living wall compared to the similar box which was covered with a living wall system without any plants and the modules were only filled with soil [46]. The results showed the living wall systems without plants have temperature reduction effect, but plants and vegetation improve the ability of temperature reduction.

Alongside vertical greenery systems ability to reduce temperatures inside the buildings, they reduce ambient temperature and surface temperatures. Price [100] investigated green facade energetics and measured the cooling effect of green facades. The results showed that the ambient air temperature, exterior surface temperature, interior air temperature and heat flux are reduced through the vertical greenery system [100]. By attention to physical structure, materials and dimensions, covering facade with plants delays solar heat shift, reduces inside temperature and provides residents relief especially after sunset [48]. Moreover, vertical greenery systems are effective elements in microclimate. A study on the climatic characteristics of nine different cities showed that using vertical greenery systems provided greater temperature reduction effect in hotter and drier climates as well as humid

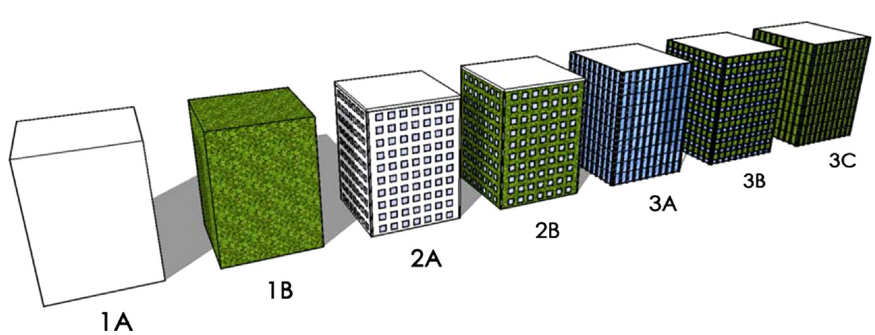


Fig. 4. (1A, 1B) Opaque walls with and without greenery. (2A, 2B) Seven windows in each storey, without greenery and with greenery cover. (3A, 3B, 3C) Full glass cover without greenery, with 50% greenery and with 100% greenery [49].

climate [72]. Much larger temperature reduction was achieved when vertical greenery systems and green roof were mixed together, but vertical greenery systems act better than green roof in canyons in all climates [72].

Attention to the results of experiments shows that vertical greenery systems are good living shading systems to reduce temperature. They protect the building facades against direct solar radiation and provide shade. Moreover, plants natural cooling effects through evaporation reduce temperature, heat flux, thermal transfer etc. and lead to reduction in cooling energy demand. Eventually, it has reduction effect on energy consumption. Comparison between the studies reveals that evaluation of thermal performance of vertical greenery systems is common by using small-scale models. By this method controlling variables is easier and the accrued results are pure results of vertical greenery systems effect. In real cases different environmental parameters are effective in temperature changes. Limited attention has been paid to the important performances of these systems. Additionally, there are limited research about vertical greenery systems energy saving capability in real cases. This issue needs more attention to improve vertical greenery systems efficiency in real cases. Therefore, study into the effective parameters of thermal performance of vertical greenery systems can optimize the thermal efficiency of these systems.

6.1.1. Thermal Performances of different kinds of vertical greenery systems

Each kind of vertical greenery system, green facade and living wall, has their own specific effect on temperature reduction. In green facades the air flows through the foliage and reduces the temperature of these systems, but in living walls based on substrate cover and the materials good shading is provided. Moreover, thermal performance of independent and self-standing vertical greenery systems are different from systems attached to the wall. Thermal properties of different vertical greenery systems should be tested to improve thermal performance of these systems.

In an experiment in Hort Park in Singapore eight different vertical greenery systems with different substrates and different plants (Table 6) were compared with a bare concrete wall as a benchmark [95]. In this comparative experiment the effect of different vertical greenery systems on ambient temperature, wall surface temperature and substrate surface temperature was studied. It was found that all vertical greenery systems reduce ambient temperatures, wall surface and substrate surface temperatures over periods of days. The best performance in temperature reduction was related to living wall and modular panel with a vertical interface which included inorganic substrate. Maximum temperature reduction was 11.5 °C and maximum ambient temperature reduction was 3.3 °C, 15 cm in front of the system [95].

Table 6
Description of vertical greenery systems in Hort Park [95].

VGS	System typology	Description	Plant size
1	Living wall – modular panel, vertical interface, mixed substrate	Combination of 2 systems: the versicell-based and ‘plug-in’ slot planter system. Versicell planters have drainage cells with selected mixture of green roof and soil planting media wrapped in geo-textile membrane while the slotted planters are mainly planter cages system.	Small to medium
2	Green facade – modular trellis	Climber plants in planters forming green screens across mesh panels on the wall.	Climber plants
3	Living wall – grid and modular, vertical interface, mixed substrate	Plant panels embedded within stainless steel mesh panels inserted into fitting frames.	Small
4	Living wall – modular panel, vertical interface, inorganic substrate	Employed the Parabienta system with a patented growing medium (composite peat moss) as a planting media inlay. The peat moss panel encased in a stainless steel cage is hung onto supports lined with integrated irrigation.	Small
5	Living wall – planter panel, angled interface, green roof substrate	This system uses a UV-treated plastic as a molded base panel with integrated horizontal planting bays.	Small
6	Living wall – framed mini planters, horizontal interface, soil substrate	Individual mini planters placed and secured onto stainless steel frame.	Small
7	Living wall – vertical moss-tile, vertical interface, inorganic substrate	Patented ceramic tiles shipped with pre-grown moss species. Suitable for creating tiling designs.	Small, custom-grown on tiles
7a	Living wall – flexible mat tapestry, horizontal interface, soil substrate	Lightweight panel comprising 2 layers of moisture retention mats secured onto a supporting grating or mesh. Plants slotted and pre-grown in between mats. Suitable for flat and curved surfaces. Allows ease of change.	Small to medium
8	Living wall – plant cassette, horizontal interface, soil substrate	Use of planters to hold wider variety of plant types and of larger sizes. Planters are secured onto the wall through hinges. Lightweight growing medium is used.	Small to medium-large

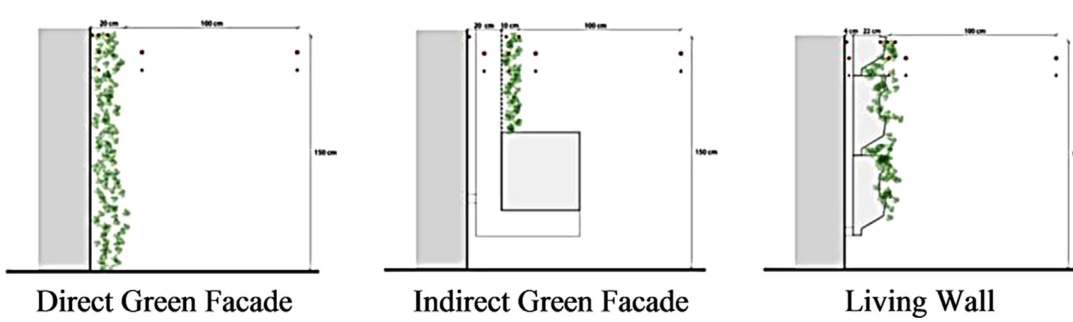


Fig. 5. Different vertical greenery systems which were applied for the Perini experiment [94].

In this experiment most of the vertical greenery systems were different kinds of living walls by differences in plants type, substrate, materials, kinds of modules and panels. There was only one green facade without sufficient plant growth. Duplication of this experiment by applying sufficient plants and adequate vegetation for green facade is recommended to compare the thermal performance of appropriate green facade with living walls in similar situations.

One similar experiment was performed to compare green facade and living wall performances in Netherlands with maritime climate [40]. In this experiment two green facades and one living wall were compared with identical areas without plants as benchmarks to understand their potential energy saving in terms of temperature reduction and controlling wind velocity [40]. One green facade was directly attached to the wall surface and another was indirect green facade standing 20 cm in front of the wall surface (Fig. 5). This study tested the effects of vertical greenery systems in different locations and the effects of different kinds of vertical greenery systems. The results of temperature reduction shows that living wall system had better temperature reduction than both green facades with direct and indirect connection to the wall surface. Living wall reduced temperature 5.0 °C while direct green facade and indirect green facade reduced temperatures 1.2 °C and 2.7 °C respectively [40]. The reason was that materials of living wall protect the wall surface against solar radiation.

Different kinds of vertical greenery systems not only have different effects on temperature reduction, but also have different effects on wind speed. The comparison between wind speed inside the foliage and 10 cm in front of the benchmarks showed that direct green facade reduced wind speed 0.43 m/s and it is going toward zero. In contrast indirect green facade reduced wind speed 0.55 m/s in the foliage, but in the cavity between green facade and wall surface wind speed increased 0.29 m/s. 0.56–10 m/s reduction in wind speed was achieved for living wall system (average 0.46 m/s) (Table 7) [40]. This qualification is good for cold climate or cold weather to use this capability as insulation to keep warm weather inside the buildings.

Other study about different performances of green facades and living walls in terms of temperature and air flow effects was performed in the tropical climate of Malaysia [96]. The difference between these two experiments is the location of vertical greenery systems. In this experiment, cable green facades and modular living walls covered the balconies of each level of a five storey office building. The comparison between green facades and living walls shows that although the air can flow through the foliage of green facades, solar radiation warmed the balcony based on limited density of foliage. To improve thermal performance of vertical greenery systems, applying both modular systems and cable systems together was the study recommendation [96].

This study not only compared thermal performances between green facades and living walls, but also compared the effects of different height of installation on their thermal performance. The number of green facades and living walls are different in each floor, therefore mean value of temperature and air velocity in floors are compared. The effects of floor height on temperature and air velocity show that floor five achieved greater solar radiation than others and had higher temperature; moreover it has maximum air velocity based on increasing air speed in height [96]. Table 8 shows the summarized results of temperature and air velocity comparison between different floors. This research is the only research that investigates the effects of different floors and heights on vertical greenery systems thermal performance.

Alongside green facades and living walls, all greeneries that can be shown in the vertical surfaces are kinds of vertical greenery systems. A 21-storey building located in Penang of Malaysia consisted of three different greenery systems in east orientation. One sky court yard is located on the 10th floor, one balcony garden is located on the 13th floor, and one green roof is located on the roof. An experiment compared air temperature, solar radiation, and wind velocity of these three kinds of greenery systems in one complex [74]. Based on the results sky court garden had lowest average air temperature of 29.0 °C and lowest mean radiant temperature of 29.9 °C. Roof top garden had highest average air temperature by 33.4 °C and highest mean radiant temperature of 43.2 °C. Balcony garden average air temperature and mean radiant temperature are 30.4 °C and 32.7 °C respectively. In air velocity measurement it was found that sky court garden had highest rate of 0.67 m/s because of tunneling effect, and balcony garden had lowest air velocity of 0.016 m/s. It can be said that there is no air velocity in balcony garden. This rate for roof top garden was 0.58 m/s [74]. The summary of results are presented in Table 9 and indicate that based on extreme solar radiation and warm air temperature in tropical climates sky court gardens are more suitable places than green roofs and balcony gardens.

Apart from these experiments, in moderate to hot climate an experiment was performed to compare one green facade, one living wall, and one fence fabric that blocked 80% of the sun-light in terms of temperature and humidity changes behind them [46]. Vertical greenery systems and fabric shade were installed on the third floor of a southwest balcony. Based on inappropriate foliage this experiment did not show desired results, but the idea of thermal comparison between vertical greenery systems and shade without any greenery is significant as well as the methodology of this experiment. The results of this research can indicate the cooling effect of plants on vertical greenery systems as well as their shading effect.

Table 7
The summary of results for Perini experiment [94].

Kind of vertical greenery systems	Temperature reduction (°C)	Wind speed reduction (m/s)
Direct green facade	1.2	0.43
Indirect green facade	2.7	0.55
Living wall	5	0.46

Table 8
The summary of results for Jaafar experiment [96].

Storey	Temperature (°C)	Air velocity (m/s)
1st Floor	29.6	0.259
2nd Floor	29.8	0.237
3rd Floor	29.7	0.220
4th Floor	29.8	0.203
5th Floor	30.7	0.263

Table 9
The summary of results for Taib experiment [74].

Parameters	Arrangement of results
Air temperature (°C)	Green roof (33.4) Balcony garden (30.4) Sky court garden (29.0)
Radiate temperature (°C)	Green roof (43.2) Balcony garden (32.7) Sky court garden (29.9)
Air velocity (m/s)	Sky court garden (0.67) Green roof (0.58) Balcony garden (0.016)

Regardless of the kind of vertical greenery systems, components such as plant type, leaf area index, materials, substrates, and the location of systems are effective parameters in temperature reduction ability. The temperature reduction benefits associated with installing vertical greenery systems are undeniable and need comprehensive study in certain climates with certain orientation.

6.1.2. The effects of orientation on vertical greenery systems thermal performances

Vertical greenery systems can be installed on each orientation of the buildings, but to determine orientation to achieve the highest energy efficiency study about latitude, climate and geographic properties are needed, and it is different from one region to another.

A study in Greek region with Mediterranean climate examined the effect of vertical greenery system in various orientation, and the results show that installing vertical greenery system respectively on west, east, south and north orientation have better temperature reduction effect [51]. A vertical greenery system can reduce cooling load of a building without windows up to 20%, 18%, 8% and 5% if installed on west, east, south and north orientation respectively [51].

The effect of orientation was tested in another experiment in dry Mediterranean continental climate [53]. Temperature reduction ability of a green facade on north-west, south-west, and south-east orientation was tested. The results show that the green facade is able to reduce temperature up to 5.5 °C peaking to 15.2 °C on south-west orientation. Moreover orientation, the effect of green facade on the temperature of cavity between greenery and wall surface were tested during winter and summer. During the winter cavity temperature was about 3.8 °C higher than the outside, and inverse during the summer where it was 1.4 °C cooler than the outside [53]. Installing vertical greenery systems by providing a microclimate between greenery and wall surface can protect the building from hot summers and cold winters. To decide the best orientation for installing vertical greenery systems each climate and weather condition should be tested separately to have maximum energy efficiency.

6.1.3. The effects of ventilation on vertical greenery systems thermal performances

Vertical greenery systems can be used as wind barriers [53], especially living walls based on substrate materials. This performance is suitable during cold seasons and it can reduce heat forfeit from inside the buildings, but during hot seasons or in hot climate ventilation is an important factor in thermal comfort and if vertical greenery systems are not designed correctly it is possible to prevent wind [76]. Applying ventilation and vertical greenery systems in appropriate ways can reduce temperature effectively. The effect of ventilation and vertical greenery system in temperature reduction is considered in an experiment in Thailand [91]. A green facade was located in front of a window of a room. First, the temperature of room was compared with the same situation without any greenery, and the experiment was repeated by adding natural ventilation to the system. It was found that green facade reduced indoor temperature and the best temperature reduction acquired was when natural ventilation was added to the system. This time the inside temperature was 9.9 °C cooler than the outside [91].

Ventilation is able to improve vertical greenery systems efficiency by correct design, but there are limited experiments that study the effects of ventilation on thermal performance of vertical greenery systems. In some experiments the importance of ventilation is mentioned, and also air velocity around the vertical greenery systems is measured and considered, but to improve the performance of vertical greenery systems by attention to ventilation more experiments should be performed by focusing on finding new ideas and methods to mix ventilation and vertical greenery systems.

6.1.4. Combination of vertical greenery systems with architectural features

Appling vertical greenery systems for their thermal benefits are not limited to stand vertical greenery systems in front of vertical surfaces. Applying these systems with different architectural features can improve the thermal performance of entire systems. One successful example is a combination of vertical greenery systems and double skin facades. Double skin facades which are also called double envelopes [101] or glass double facades [102] have acoustic, moisture, fire safety and visual comfort advantages as well as thermal benefits [102]. They are described as two layers of facade separated by an air gap [103]. The blinds are located inside the air gap and protect the building from solar heat and play a vital role in protecting the building against solar energy. In this way, blinds have high temperature and it is not pleasant in warm duration. Therefore, an experiment used vertical greenery system in the air gap of double skin facade instead of blinds (Fig. 6) to improve double skin facade performance by using natural benefits of plants [104].

The results of experiment show that vertical greenery system reduce the temperature of the whole system, and sometimes the temperature of plants in double skin facade is half the temperature of blinds. By using plants in double skin facade the cooling capacity reduced around 20%, the same as reduction in energy consumption of cooling system [104]. Using plants in double skin facade have a few problems such as difficulty in controlling light transmission and maintenance control.

Applying vertical greenery systems to improve thermal performance of the buildings and structures should be tested in other architectural features to improve their efficiency. Vertical greenery systems can offer new genuine form and present intelligent ideas to reduce temperatures and enhance thermal performance. One experiment was performed in Maryland to approve green clock thermal performance [92]. Green clock is vine canopy suspended above the roof surface and the aim of the experiment was to justify this system instead of green roof, but in this case it covered both roof and facades. The results show that green clock reduced inside temperature up to 3.0 °C [92]. Covering the entire building with green clock is not easy especially in urban areas due to urban density, but the idea and examination of methods to apply vertical greenery systems in buildings and architectural features to reduce temperature is an important way to find new and innovative methods.

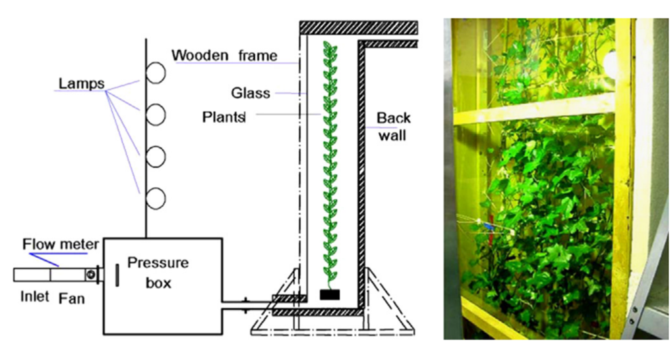


Fig. 6. Laboratory test facility of the double skin facade with plants for Stec experiment [104].

6.2. Other performances of vertical greenery systems

The focus of this writing is on vertical greenery system temperature and energy reduction, but to authenticate these systems it is acceptable to mention experiments about their other performances such as noise annoyance reduction, or the performance of substrates. Noise problems occur due to urbanization and growing population in cities and urban areas. Transportation and vehicles provide noise problems especially in crowded areas. Moreover, factories and industrial regions are noisy places. In a survey questionnaire noise pollution was 30–50% of respondents' neighborhood problem [84]. It is proved that vicinity of urban green areas reduce noise annoyance at home [105], but acoustic influence of vertical greenery systems was tested in Singapore and the results showed that vertical greenery systems are able to reduce noise annoyance [58]. Other experiments performed in the United States showed that vertical greenery systems absorb sound and reduce sound transmission [46]. The kinds of vertical greenery systems and plant types are effective parameters to noise reduction results, and they should test to find best system to control noise annoyance.

Other important issues in vertical greenery systems are attention to active and passive systems. The difference between active and passive systems is that active systems or biofiltration have a ventilator that blows air across substrate and plants, while passive system has only the vertical greenery system and no extra cooling system. In an experiment polyester, polyurethane, and polyamide–polypropylene were three synthetic substrates used in an active living wall to compare their water volume retained, pressure drop, saturation efficiency and water consumption [106]. The results show that the best performance in saturation efficiency was for polyamide–polypropylene with high pressure drop, average water volume retained, and low water consumption. Polyurethane has least air flow and also least pressure drop. It has highest water consumption and also highest water volume retained. Polyester has the worst saturation efficiency and also the worst water volume retained, average pressure drop and high water consumption [106].

Different aspects of vertical greenery systems should be tested to find the more suitable system. In this way it is possible to utilize efficient and operant system to reduce energy.

7. Summary and recommendations

Sustainable methods are needed to control environmental damage and reduce energy demand. There are some sustainable remedies like using bioclimatic architecture or solar architecture [107], but using plants and greenery is economical and easy. Vertical greenery systems include vegetation grown on vertical surfaces. Installing vertical greenery systems by blocking extreme solar radiation and using plants natural cooling effects based on evaporation and transpiration reduce temperature. Moreover, plants reduce solar re-radiation and diminish the temperature of environment. The cooling effects of vertical greenery systems reduce cooling energy demand, and cause energy efficiency in buildings which is the building's ability to operate and function with minimum energy consumption. These abilities of vertical greenery systems deliver numerous environmental and economic benefits, but general awareness is about social benefits and esthetic impacts of these systems. There is no great agreement about environmental and economic advantages of vertical greenery systems. It shows the need of improving general awareness about these systems environmental and economic benefits to increase people's tendency to install vertical greenery systems not only for their esthetic views.

To apply vertical greenery systems for different purposes particular attention to select suitable plants and leaf area index properties are needed as well as attention to maintenance and growth to achieve high shade rate. The properties of plants should be tested in different climates and different weather conditions. Moreover, the orientation of vertical greenery systems on building walls should be tested in different climates separately to find appropriate orientation to install vertical greenery systems to achieve maximum efficiency. In applying vertical greenery systems for its temperature reduction ability adding ventilation to the systems can improve the system efficiency, but there are limited research and studies about integrating the performance of ventilation and vertical greenery systems together. For future experiments finding innovative methods to apply ventilation and vertical greenery systems performance is highly recommended. Alongside ventilation, combination of vertical greenery systems and different architectural features is recommended to find new techniques and methods to improve temperature reduction ability and efficiency of vertical greenery systems. Study about different materials of green facades and living walls and also attention to substrates are recommended to find the best material for improving the thermal performance of vertical greenery systems.

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